

## Disease Progress Models

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## Motivations for Disease Progression Models

- Visualization of the time course of disease in treated and untreated conditions
- Simulation of
  - Future course of disease
  - Various disease interventions to evaluate treatment options
  - Clinical trial designs
- Framework for regulatory submissions

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## New Objectives for Clinical Trials

- In a confirmatory trial, the purpose of that trial is to test the null hypothesis.
  - Clinical trials usually focused on testing null hypothesis because there is an alternative model that can be accepted in place of the null model.
- Testing the null hypothesis is an easy question to answer robustly
  - Traditionally statistics has been focused on questions that are easy to answer but not necessarily on answering the right questions.
- "Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise." - Tukey

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## New Objectives for Clinical Trials

- Developing an exposure response surface is not an easy question to answer but maybe it's the right question to ask
  - Usually requires assumptions which weakens the robustness of the answers.
    - Assumptions reduce inferential certainty because if the assumptions are wrong, then the model based conclusions are wrong.
    - It is the quality of the attendant assumptions, not their existence, that is the issue.
  - A summary of the surface function, such as an average over the response surface can provide robust answers to simpler questions.
    - The margins of a high dimensional surface are usually well estimated, even with modeling.
    - If a model is used to address the right question, the answer will have uncertainty associated with that answer, but summarizing or integrating over that model in order to answer simpler questions can still provide robust answers.

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## Evaluating a Response Surface

- During drug development patients can have different responses
  - Differing sensitivity contributes to the variability (e.g. noise) in the outcome of the study.
    - Impossible to study all combinations of doses or treatments by patient type
  - Need to develop the dose response surface without data from every type of patient given every dose level and duration of therapy
- The time course of disease in the untreated patient is also variable
  - Characterizing the time course of placebo response allows better evaluation of drug effect
- Clinical markers of outcome are inherently variable as well
  - Residual error for HAMD is notable
  - Repeated measures assessments are generally more able to evaluate the central trend of a response
- Model based evaluations provides a basis for developing exposure response surface by making scientifically valid assumptions

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## Evaluating a Response Surface

- Models increase the amount of information recovered from a clinical trial.
  - Information obtained from any scientific study can be detected based on the ratio of signal to noise.
  - In any given study, the information is the total variation in the data, the signal is the variation due to identifiable causes such as differences in dose, and the noise is the residual or unexplained variation.
  - Models increase information by turning noise into signal by providing a basis for explaining the variation

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## Clinical Pharmacology

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Disease Progress + Drug Action\*

\*It also follows that

"Drug Action" = Drug Effect + Placebo Effect

- The effect of a drug involves understanding the progression of the disease and the effect of placebo as well as the effect of administering a test drug

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## PKPD Models

### • Pharmacokinetic (dose, concentration, time)

- drug disposition in individuals & populations
- disease state effects (renal & hepatic dysfunction)
- intervention effects (hemodialysis)
- concurrent medication effects
- pharmacogenetic influences

### • Pharmacodynamic (dose or concentration, effect, time)

- physiologic & biomarkers
- surrogate endpoints
- clinical effects and endpoints

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## Disease Progression Model

### • Quantitative model that accounts for the time course of disease status, $S(t)$ :

- "Symptoms" - measures of how a patient feels or functions ("*clinical endpoints*")
- "Signs" - physiological or biological measurements of disease activity ("*biomarkers*")
  - "*Surrogate Endpoints*" (validated markers predictive of, or associated with Clinical Outcome)
  - "*Outcomes*" (measures of global disease status, such as pre-defined progression or death)

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## An Old Model with a New Meaning

$$E \approx E_0 + \frac{E_{\max} \cdot C_p}{EC_{50} + C_p}$$

Disease Status

Disease Progression

Drug Action

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## Components of a Disease Progression Model

$$S(t) = \text{Baseline} + \text{Natural History} + \text{Placebo} + \text{Active}$$

- Baseline Disease State,  $S_0$
- Natural History
- Placebo Response
- Active Treatment Response

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## Placebo Response

- Placebo response is the change in disease progression in untreated patients who are randomized to receive placebo as treatment for their disease in a clinical trial
  - Usually transient improvement in clinical status followed by relapse to pre-study status
  - In depression trials, the placebo response may be at least partly due to the interaction and attention that the enrolled patients receive regardless of treatment
    - The placebo response time course in depression trials appears to be somewhat dependent on study design - more intensive clinical visits usually result in greater placebo response that is more persistent
- Placebo response tends to be variable both in magnitude and duration and is often more notable when the clinical status is evaluated subjectively

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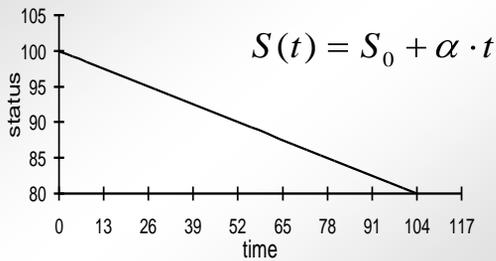
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## Linear Disease Progression Model

(adapted from Holford 1999)




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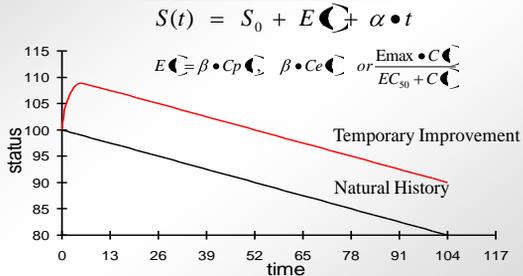
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## Linear Disease Progression Model with Symptomatic ("Offset") Placebo or Active Drug Effect

(adapted from Holford 1997 & 1999)




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## Handling Pharmacokinetic Data for Disease Progress Models

- Use actual measured concentrations
  - This is easy to do
- Use a "Link" model to create a lag between observed concentrations and observed effect
  - This is more "real" as the time course for change in disease status is usually not the same as the time course of the drug

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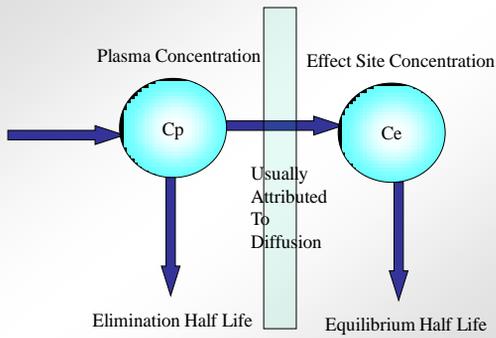
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## Effect Compartment




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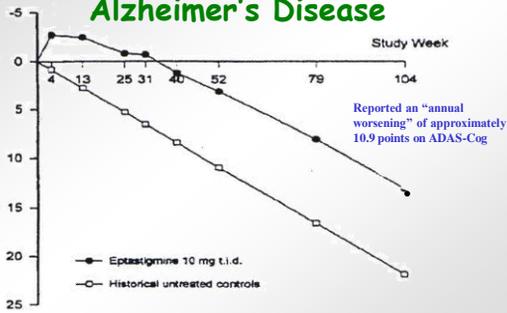
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## Evaluation of Effect of Eptastigmine on Trajectory of Alzheimer's Disease



Inhimo BP, Verdelli G, Martelli P, Marchesini D. "Two year treatment of Alzheimer's disease with eptastigmine". The Eptastigmine Study Group. Dementia and Geriatric Cognitive Disorders 1999;10(2):139-147

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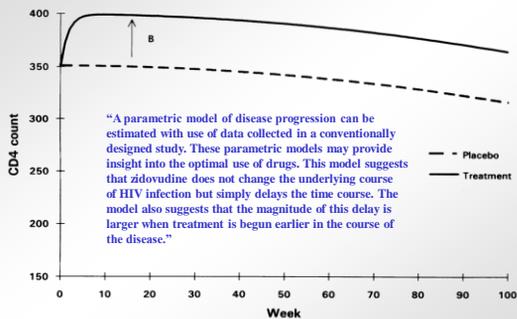
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## AZT Treatment Effect on HIV



Sale M, Steiner LB, Volberding P, Blaschke TF. "Zidovudine response relationships in early human immunodeficiency virus infection. Clin Pharmacol Ther. 1993 Nov;54(5):556-66.

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## Tacrine Treatment of Alzheimer's Disease

- Baseline Disease State:  $S_0$
- Natural History:  $S_0 + \alpha \cdot t$
- Placebo Response:  $\beta_p \cdot C_{e,p}(t)$
- Active Treatment Response:  $\beta_a \cdot C_{e,A}(t)$

Holford & Peave, Proc Natl Acad Sci 89 (1992);11466-11470

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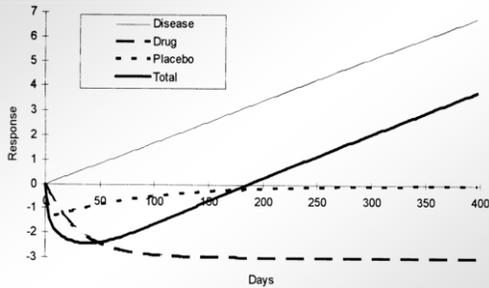
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## Tacrine Treatment of Alzheimer's Disease



Holford & Peave, Proc Natl Acad Sci 89 (1992);11466-11470

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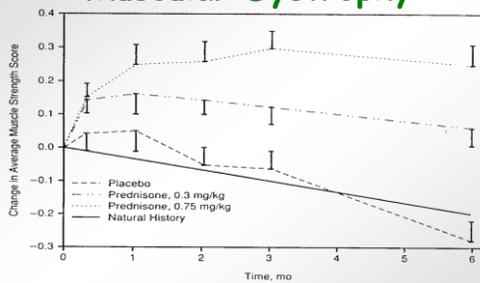
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## Prednisone Treatment Effect on Muscular Dystrophy



Griggs et al. Arch Neurol (1991); 48: 383-388

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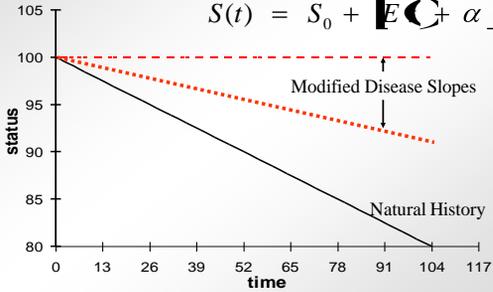
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### Linear Disease Progression Model with Disease Modifying ("Slope") Active Drug Effect

adapted from Holford 1999

$$S(t) = S_0 + [EC + \alpha] \cdot t$$




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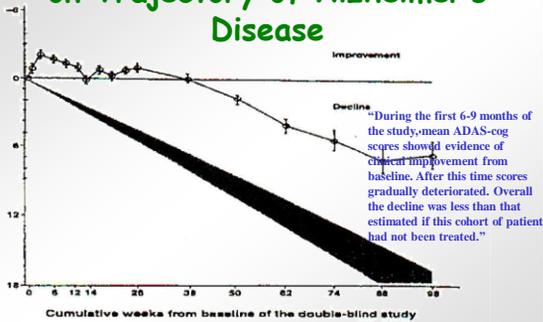
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### Evaluation of Effect of Donepezil on Trajectory of Alzheimer's Disease



Rogers SL, Doody RS, Pratt RD, Ieri JR. "Long term efficacy and safety of donepezil in the treatment of Alzheimer's disease: final analysis of the results of a US multicentre open label extension study". European Neuropsychopharmacology 2000 May;10(3):195-203

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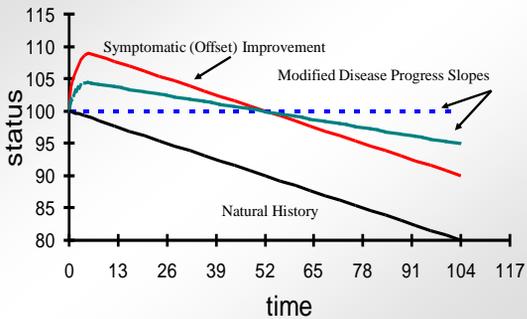
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### Alternative Drug Effect Mechanisms Superimposed on a Linear Natural History Disease Progression Model

adapted from Holford 1999




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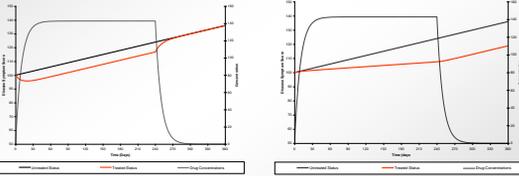
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## Onset and Offset of Drug Effect Helps Distinguish Symptomatic from Disease Modifying Effects




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## Asymptotic Progression Models

- Useful if the marker of disease progression has a natural limit (0 or some other value)
- Zero Asymptote ( $S_0, k_{prog}$ )
  - Spontaneous recovery or return to a 0 value of disease progression marker
  - Several functions used to describe
    - Exponential
    - Emax functions
- Non-Zero Asymptote ( $S_0, S_{ss}, k_{prog}$ )
  - Progression to maximal or "burned out" state ( $S_{ss}$ )
  - Several functions used to describe
    - Emax functions
    - Growth functions

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## Dealing with Asymptotic Functions

- Both zero and nonzero asymptotic models can be altered to include
  - Offset Pattern
  - Slope Pattern
  - Both Offset and Slope Patterns
- Selection of the function depends on nature of the marker of disease progression being evaluated

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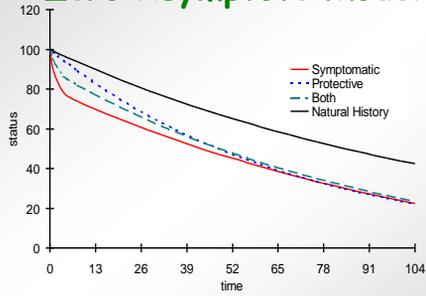
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## Zero Asymptote Model




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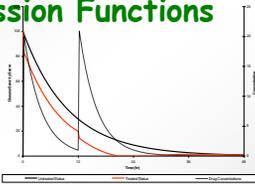
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## Exponential "Zero Asymptotic" Disease Progression Functions

$$S(t) = S_0 \cdot e^{-k_{prog} \cdot t}$$

Zero Asymptote Disease Progression Function

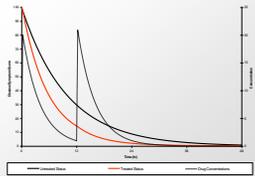


$$S(t) = S_0 \cdot e^{-k_{prog} \cdot t} - E \cdot \left[ \frac{1 - e^{-k_{prog} \cdot t}}{k_{prog}} \right]$$

Zero Asymptote Disease Progression Function  
Symptomatic (Offset) Drug Effect

$$S(t) = S_0 \cdot e^{-k_{avg} \cdot t + E \cdot \left[ \frac{1 - e^{-k_{prog} \cdot t}}{k_{prog}} \right]}$$

Zero Asymptote Disease Progression Function  
Disease Modifying Drug Effect




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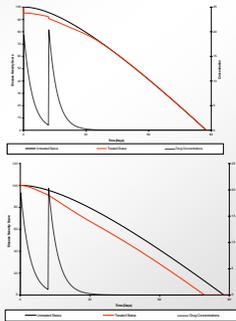
## Emax "Zero Asymptotic" Disease Progression Functions

$$S(t) = S_0 + \frac{S_{max} \cdot t}{S_{50} + t}$$

$$S(t) = S_0 + \frac{S_{max} \cdot t}{S_{50} + t} + E \cdot \left[ \frac{1 - e^{-k_{prog} \cdot t}}{k_{prog}} \right]$$

$$S(t) = S_0 + \frac{S_{max} \cdot \left( 1 + E \cdot \left[ \frac{1 - e^{-k_{prog} \cdot t}}{k_{prog}} \right] \right) \cdot t}{S_{50} + t}$$

$$S(t) = S_0 + \frac{S_{max} \cdot t}{S_{50} \cdot \left( 1 + E \cdot \left[ \frac{1 - e^{-k_{prog} \cdot t}}{k_{prog}} \right] + t \right)}$$




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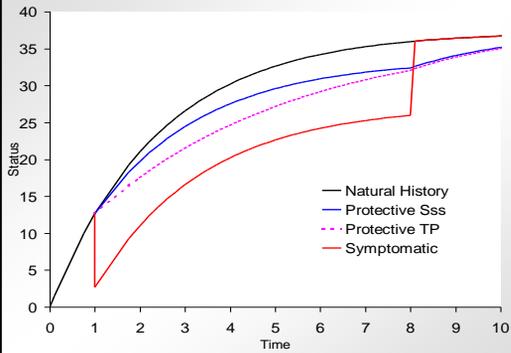
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## Non-Zero Asymptote Model




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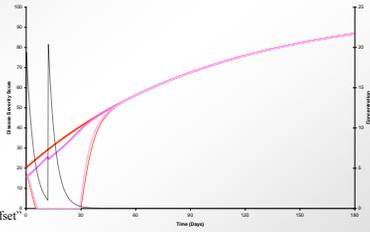
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## Non-Zero Asymptote Models

$$S(t) = S_0 \cdot e^{-k_{prog} \cdot t} + S_{SS} \cdot (1 - e^{-k_{prog} \cdot t})$$



Effect of drug can be added as "offset" for symptomatic improvement

If the drug has disease modifying activity, the effect can reduce Sss or it can slow kprog




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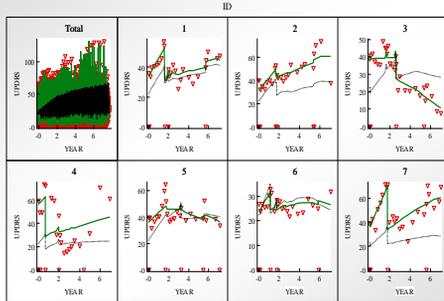
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## PSG DATATOP Cohort




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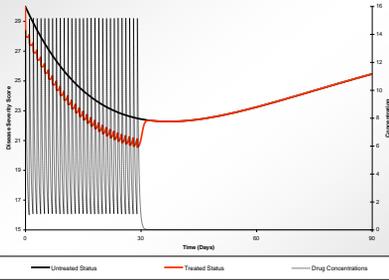
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## Inverse Bateman Function



$$HAMD(t) = S_0 - \frac{Drec \cdot Krec}{Krec - Kon} \cdot \exp(Kon \cdot t - Krec \cdot t)$$

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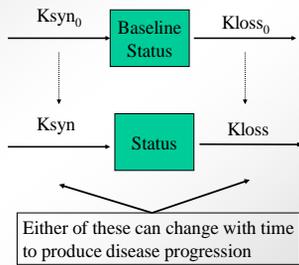
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## Physiological Models of Disease Progress




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## Physiological Models of Disease Progress

$$\frac{dS}{dt} = K_{syn} - k_{loss} \cdot PDI \cdot S$$

Disease is caused by build up or loss of a particular endogenous substance

$$K_{loss} = K_{loss0} \cdot \left( 1 + (Maxprog - 1) \cdot \left( 1 - e^{-\ln(2)/S_{50loss} \cdot t} \right) \right)$$

$$PDI = 1 - \frac{C_{e,A}}{C_{50} + C_{e,A}}$$

Drug action can be described using delay function such as an effect compartment

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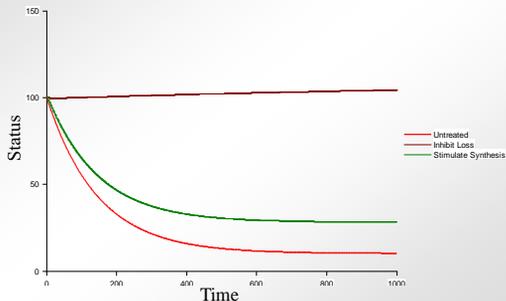
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## Disease Progression Due to Decreased Synthesis




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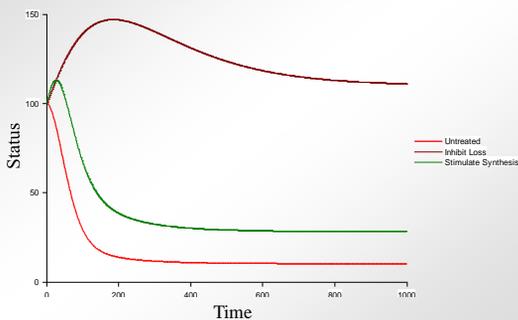
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## Disease Progression Due to Increased Loss




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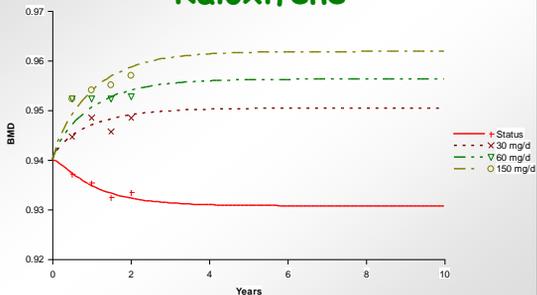
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## Bone Mineral Density Change with Placebo and 3 doses of Raloxifene




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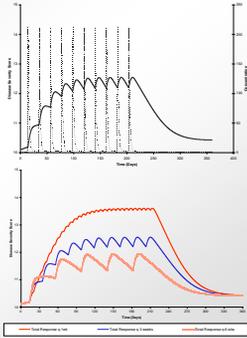
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## Cell Transit Models

- Utilizes a string of compartments to implement a delay to response
- Useful for modeling anemia and other chronic progressive diseases




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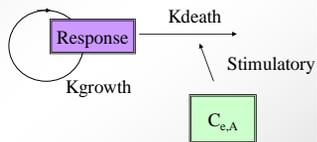
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## Models Describing Growth

$$\frac{dR}{dt} = k_{growth} \cdot R - k_{death} \cdot R \cdot C_{e,A}$$



First order kinetics for input!  
Effect of drug stimulates loss of response (R)

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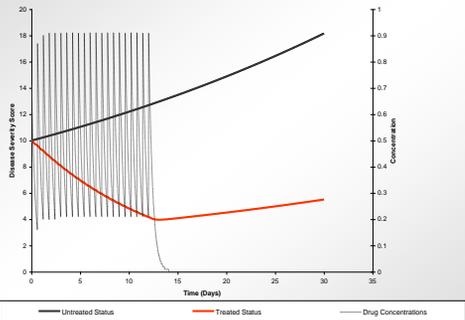
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## Growth Functions




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## Gompertz Growth Function Models

$$\frac{dR_S}{dt} = K_{RS} \cdot Rr + \beta \cdot R_S \cdot \left( \beta_{\max} - R_S \right) \cdot \left[ K_{SR} + \left( 1 + \frac{E_{\max} \cdot C_{e,A}}{EC50 + C_{e,A}} \right) \cdot K_{SO} \right] \cdot R_S$$

$$\frac{dRr}{dt} = K_{SR} \cdot R_S - K_{RS} \cdot Rr$$

Describes the Formation of Two Responses: Sensitive (Rs) and Resistant (Rr)  
 Defines a Maximal Response  
 Drug Effect is Delayed via Link Model and Limited via Emax Model

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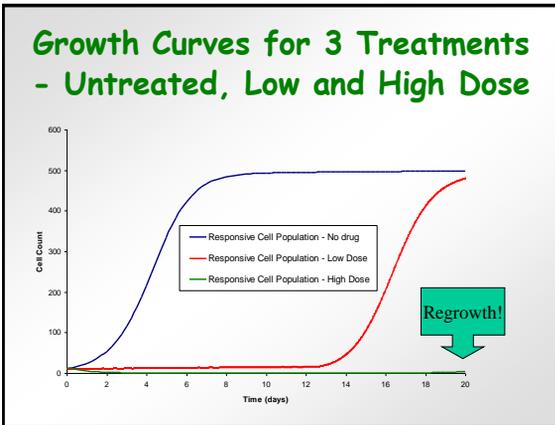
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## Growth Curves for 3 Treatments - Untreated, Low and High Dose




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## Using Survival Functions to Describe Disease Progress

- Empirical means of evaluating the relationship between the drug effect and the time course of disease progress
- Links the pharmacodynamics to measurement of outcome

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## Survival Function

- $S(t) = P(T > t)$
- Monotone, Decreasing Function
- Survival is 1 at Time=0 and 0 as Time Approaches Infinity.
- The Rate of Decline Varies According to Risk of Experiencing an Event
- Survival is Defined as

$$S(t) = \exp(-H(t))$$

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## Hazard Functions

- Hazard Functions Define the Rate of Occurrence of An Event
  - Instantaneous Progression
  - PKPD Model Acts on Hazard Function
- Cumulative Hazard is the Integral of the Hazard Over a Pre-Defined Period of Time
  - Describes the Risk
  - Translates Pharmacodynamic Response into a Useful Measure of Outcome
    - Assessment of Likely Benefit or Adverse Event
    - Comparison With Existing Therapy

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## Hazard Functions

- Define "T" as Time To Specified Event (Fever, Infection, Sepsis following chemotherapy)
  - T is Continuous (i.e. time)
  - T is Characterized by:
    - Hazard: Rate of Occurrence of Event
    - Cumulative Hazard or Risk
    - Survival: Probability of Event NOT Occurring Before Time = t

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## Hazard Functions

- Hazard is Assumed to be a Continuous Function
  - Can be Function of Biomarkers (e.g. Neutrophil Count)
- Hazard Functions can be Adapted for Any Clinical Endpoints Evaluated at Fixed Time Points (e.g. During Chemotherapy Cycle)
- The Hazard Function is Integrated Over Time to Yield Cumulative Probability of Experiencing an Event by a Specified Time (Risk).

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## Using Hazard Functions in PK/PD Models

- If Hazard Function is Defined as a Constant Rate "K" Such that

- Then the Cumulative Hazard is  $h(t) = k$

$$H(t) = \int_0^t K dt = Kt$$

- Survival is

$$S(t) = \exp[-Kt]$$

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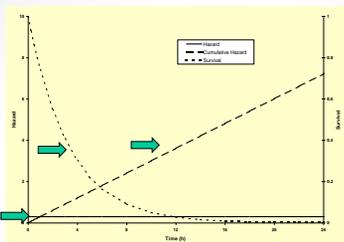
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## Hazard, Cumulative Hazard and Survival

- In This Example Hazard Remains Constant
- Cumulative Hazard (Risk) Increases With Time
- Surviving Fraction Drops




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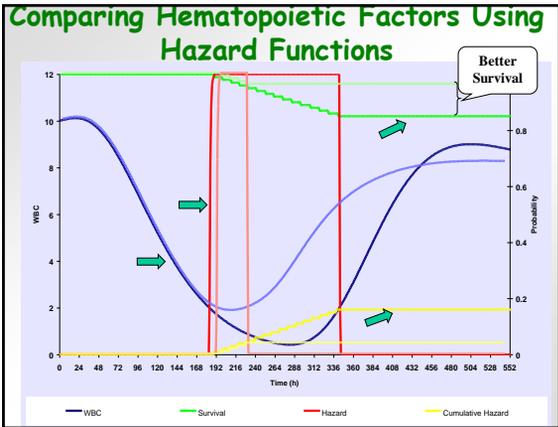
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## Disease Progress Models

- Alzheimer's Disease
  - Linear: Drug effects symptomatic
- Diabetic Neuropathy
  - Linear: Drug effect both?
- Parkinson's Disease
  - Asymptotic: Drug effect both?
- Osteoporosis
  - Inhibition of Bone Loss (estrogen)
- In most cases, the functions used to describe the trajectory of the disease marker are empirical. Whenever possible, mechanistic models should be used - but for most diseases mechanisms are not always clearly understood

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## Summary

- Accounting for Disease Progress is Important For the Analysis of Drug Effects
  - Better Able to Discern True Effect
  - Improves Reliability of Simulation Work
  - Developing New Drug Candidates
  - Visualize the Drug Use Better
  - Convert Data into Understanding!
- Issues Associated With Building Disease Progress Models
  - Lack of Available Data for Untreated Patients
  - Time Required to Collect Data
  - Variability Inherent in Data May Require Large Numbers of Subjects to Determine Parameters Accurately

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